Development of a Lunar Lander Modeling and Simulation Capability

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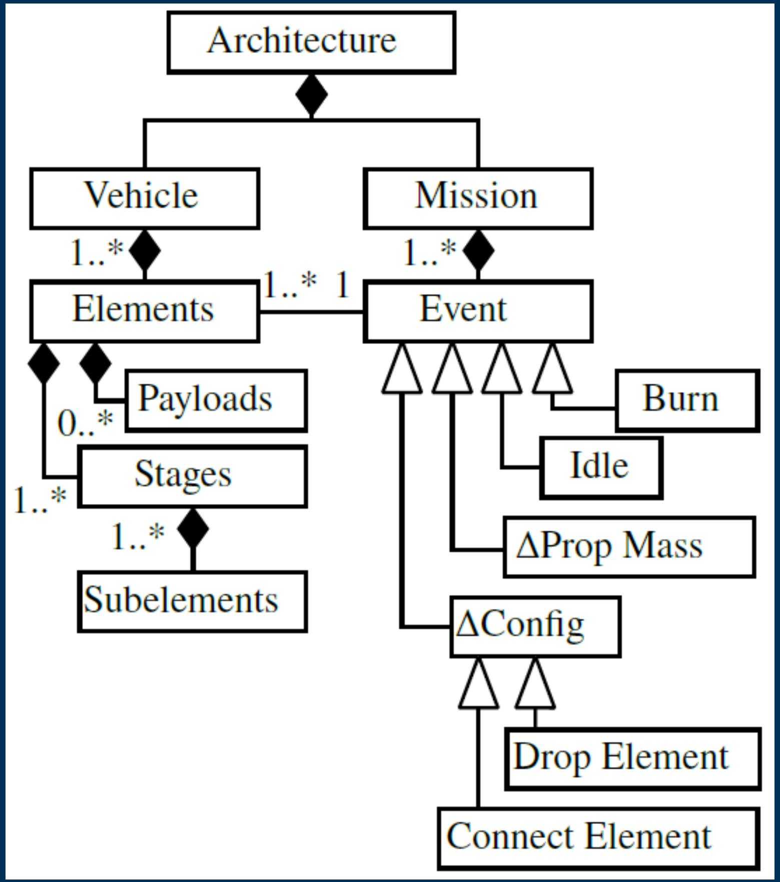
Dynamic Rocket Equation Tool (DYREQT)

- DYREQT is a specialization of OpenMDAO for space transportation systems
- A space system architecture is comprised of
  - Vehicle Definition
    - Set of elements (e.g. payloads and stages)
      - A stage is comprised of tanks, payloads, propulsion systems, etc.
      - These models are added as subelements under an element
      - Subelements can utilize external codes
  - Mission Definition
    - CONOPS defined by four general event types
      - Burn– propulsive ΔV
      - Idle– passage of time
      - Inert mass change (e.g. docking)
      - Propellant mass change (e.g. refueling)
- While DYREQT has been used for many space systems, the goal of this paper is to demonstrate the sizing and synthesis of a lunar lander



Contributing Analyses

- Each subsystem module takes in a set of inputs
- Subsystems are sized using:
  - Historical data
  - Physics-based equations
  - Mass estimating relationships
- Subsystem outputs:
  - Mass
  - Power requirements
  - Thermal load

Avionics

- Sizes hardware associated with sensing, actuating, and communication
- Based on mass and power data of flight-certified, commercially available hardware

Power

- Includes the generator, power storage, and regulation / distribution
- Primary power generator sized to satisfy total power requirement for the lander
- Power storage sized to provide power during eclipse

Structures

- Percentage of the vehicle dry mass determined from data collected on a variety of space systems

Tanks

- Sizes all storage tanks (propellant and pressurant)
- Includes tanks, liquid acquisition devices (LAD), miscellaneous hardware, additional pressurant and propellant masses

Thermal Control

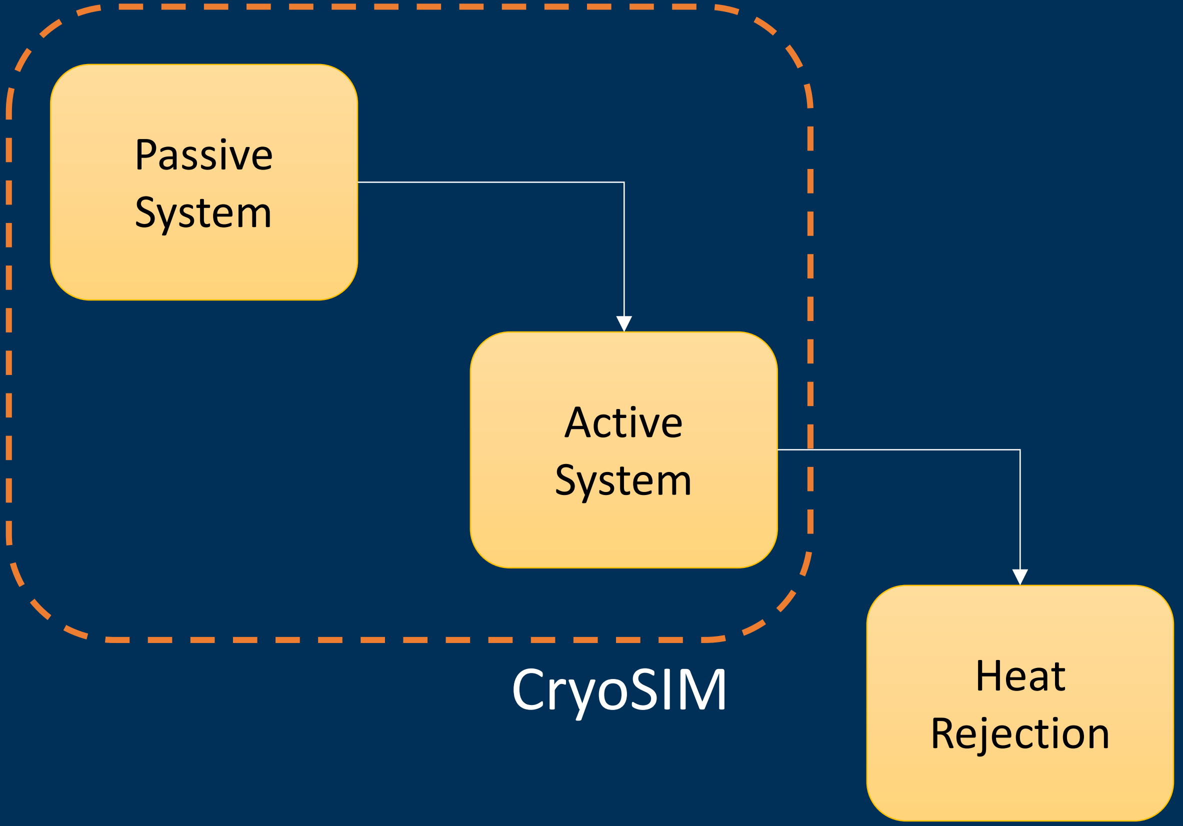
- Sizes passive and active CFM systems and the spacecraft thermal rejection system
- Sizing of CFM systems accomplished via NASA's Cryogen Storage Integrated Model (CryoSIM)

Engines

- Sizes bipropellant liquid engines
- Subsystem mass includes the engine(s), propellant management hardware, and miscellaneous components

Thermal Control Subsystem Sizing

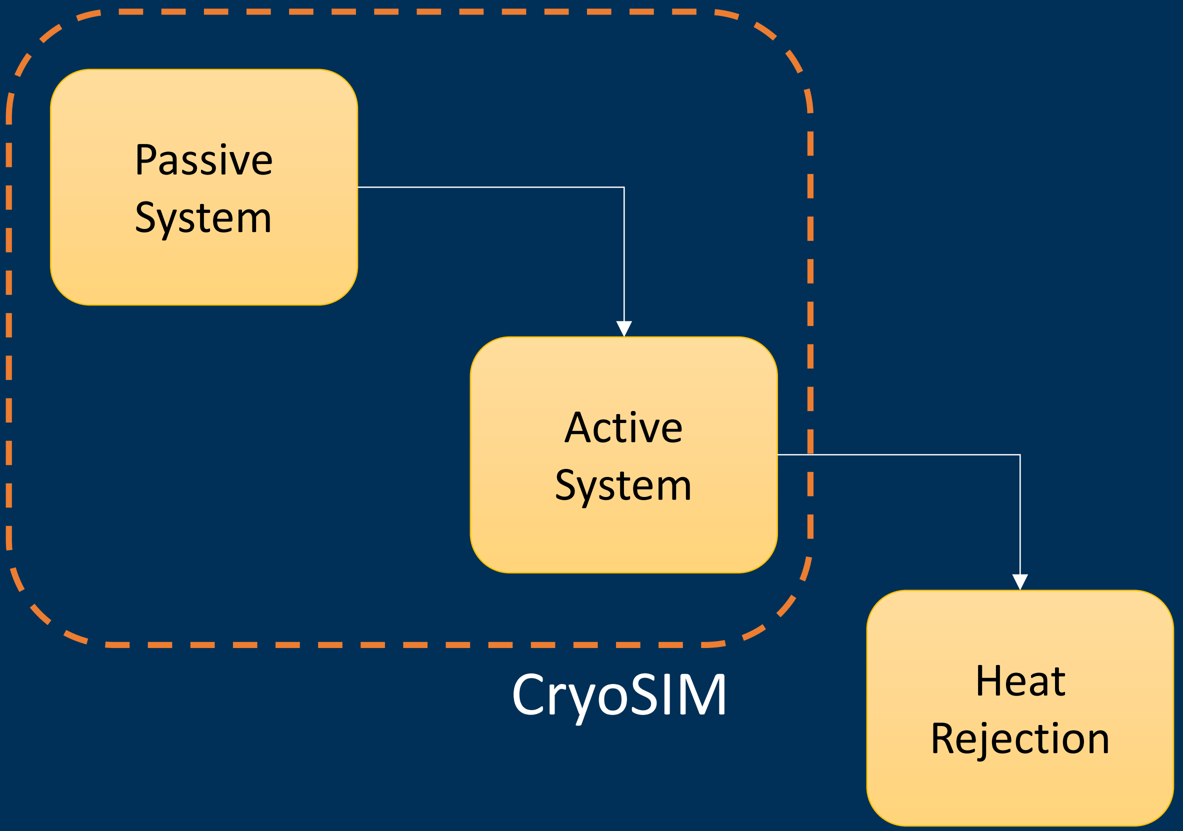
- Sizing of thermal control system occurs in three parts:
  - Passive system
  - Active system
  - Heat rejection
- Sizing requires the following information:
  - Thermal environment (mission)
  - Tank geometry
  - Propellants
  - CFM approach (active or passive)
- Passive and active CFM systems sized using CryoSIM



Passive CFM Sizing

- Passive system consists of:
  - Variable density multi-layer insulation (MLI)
  - Spray on foam insulation (SOFI)
  - Heater*
  - Mass gauging (MG) device

- Outputs:
  - Mass
  - Power requirement
  - Total heat load on the tank
  - (Passive) boil-off rate



***Storable propellants**

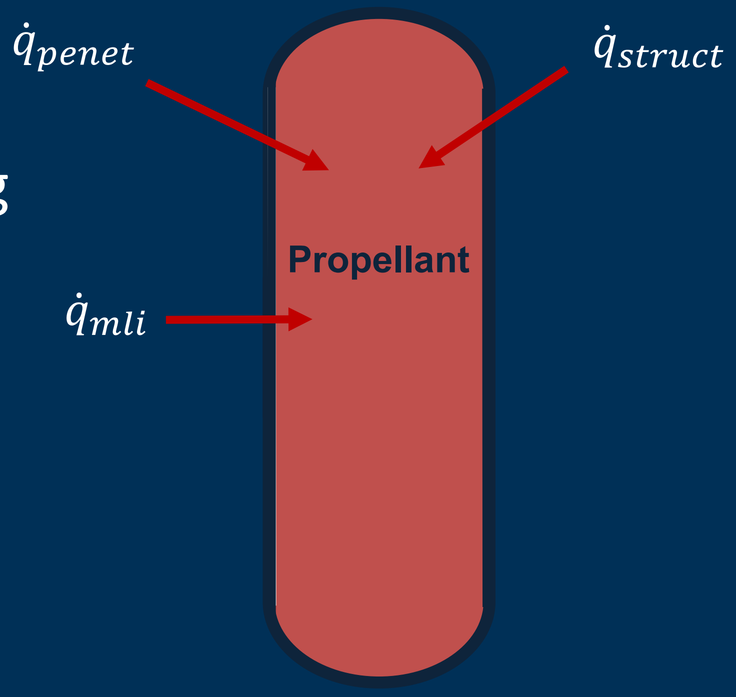
Passive CFM Sizing: Boil-Off

- The propellant boil-off rate is determined by the total heat entering the tank ($\dot{q}_{total}$):

$$\dot{m} = \frac{\dot{q}_{total}}{h_{vap}} \quad \textbf{kg/d}$$

- Three major sources of heat penetrating the tank and entering the propellant:
  - Heat penetrating the MLI
  - Thermal conduction from tank support structure and penetrations
- Heat through the MLI calculated via the Modified Lockheed equation
- Temperature of the structure and penetrations is determined by the following:

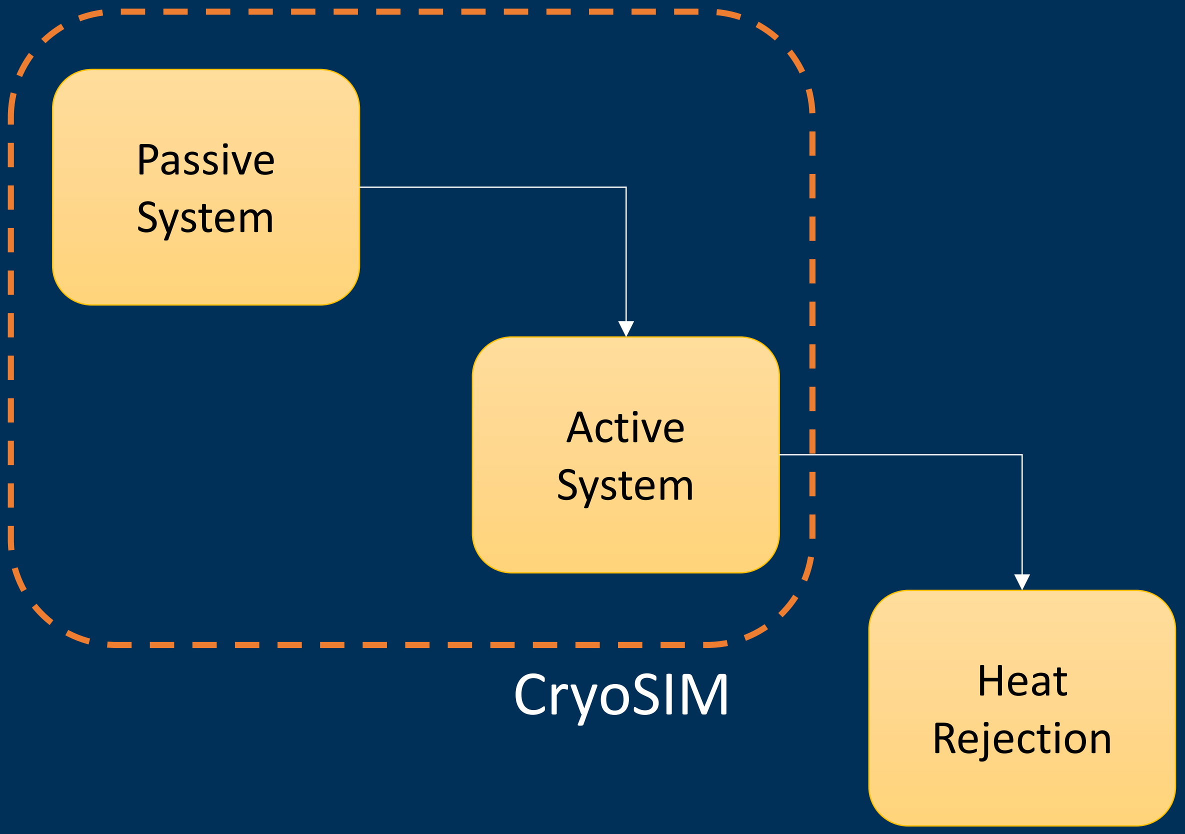
$$T_{int} = \begin{cases} \frac{2}{3}\left(T_{high} - T_{low}\right) + T_{low}, & colder\ fluid \\ T_{high}, & warmer\ fluid \end{cases}$$



$$\dot{q}_{total} = \dot{q}_{mli} + \dot{q}_{struct} + \dot{q}_{penet}$$

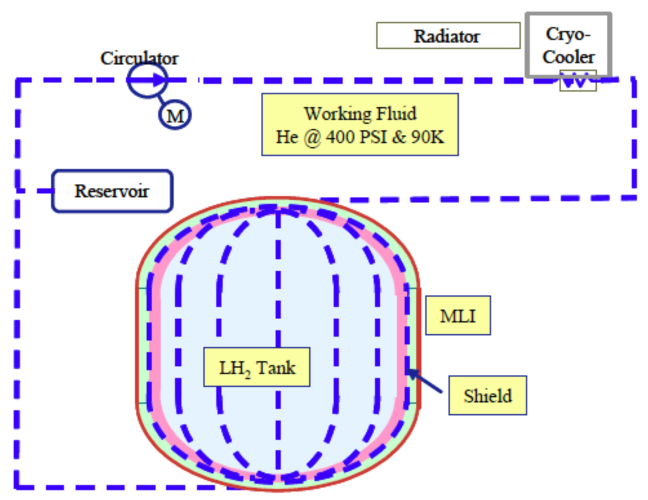
Active CFM Sizing

- Active CFM system consists of:
  - Cryocooler
  - Broad area cooling (BAC) shield
- Cryocoolers are sized to completely remove the heat entering the tank
  - Receives $\dot{Q}_{total}$ from passive sizing routine
- CryoSIM supports the analysis of the following propellant combinations and CFM configurations:
  - ZBO LOX/LCH4
  - ZBO LOX/LH2
  - RBO LOX/LH2



Broad Area Cooling

- Provides additional cooling by adding a gas cooled shield
  - LH2 tank: shield is incorporated within the MLI
  - LOX and LCH4 tank: shield applied to the external surface of the tank wall
- Concept consists of a cryocooler, a circulator, and a cooling tube network
  - Uses the same coolant to cool both fuel and ox tanks
  - Additional mass from shield and tubing



[1]Plachta, D. W., et al. "Cryogenic Propellant Boil-Off Reduction System." *AIP Conference Proceedings.* Vol. 985. No. 1. AIP 2008.

CFM Configurations

- LOX/LCH4 ZBO: 90 K cryocooler LOX + dedicated shield (@ 90 K)
  + 90 K cryocooler LCH4 + dedicated shield (@ 90 K)
- LOX/LH2 RBO: 90 K cryocooler LOX + dedicated shield (@ 90 K)
  + 90 K cryocooler LH2 + dedicated shield (@ 90 K)

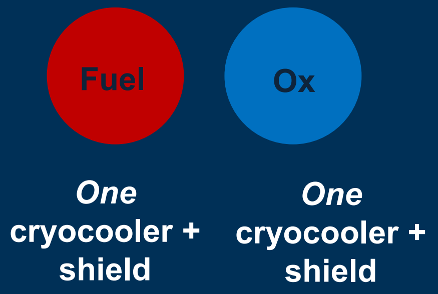
Same configuration (first two bullets)

- LOX/LH2 ZBO: 90 K cryocooler LOX + dedicated shield (@ 90 K)
  + 90 K cryocooler LH2 + dedicated shield (@ 90 K)
  + 20 K cryocooler LH2 + dedicated shield (@ 20 K)

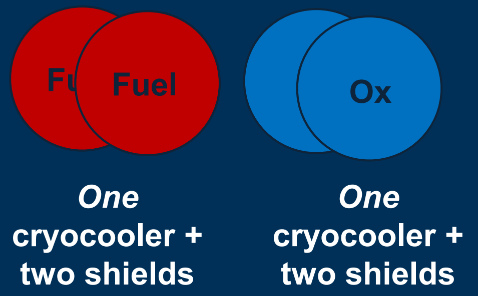
Distributed Cooling

- The heat load for two tanks are sent to a single cryocooler:
  - Maximizes cooling benefits
  - Minimizes mass penalty
- Requires an even number of tanks for propellant in question
  - No cross-sharing of cryocoolers among fuel and ox tanks
- Odd number of tanks: assign a single cryocooler per tank

Two tank configuration

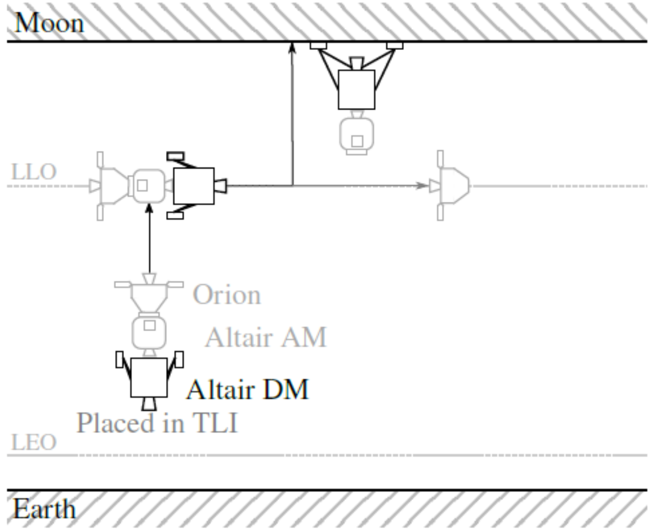


Four tank configuration



Validation Altair Lunar Lander Descent Module

- Validation of the environment was performed using data from the Altair lunar lander descent module
- The mission Concept of Operations (CONOPS) was modeled after a standard lunar sortie mission
  - The Altair is launched aboard Ares V heavy lift LV
  - A few days later Orion and Crew launch aboard Ares I
  - In LEO, Orion and crew detach from Ares I and dock with Altair on Ares V
  - Ares V performs Trans-Lunar Injection (TLI)
- The Altair DM is responsible for all propulsion maneuvers beyond TLI
  - LOI → LLO
  - Crew transfer from Orion to Altair AM
  - Orion detaches from Altair
  - LLO → lunar surface



Event	Propulsion System	Metric
LEO Loiter		4 days
TCM Burns	RCS	25.4 m/s
Lunar Transit		4 days
LOI Settling Burn	RCS	0.6 m/s
LOI-1	MPS	326 m/s
LOI-2	MPS	59 m/s
LOI-3	MPS	565 m/s
LOI Dispersion	MPS	2.6 m/s
LOI Clean Up	RCS	7.0 m/s
LLO Minimum Loiter		1 day
LLO Altitude Maintenance	RCS	10.1 m/s
LLO Extended Loiter		3 day
Detach Orion		
LLO Altitude Maintenance	RCS	30 kg/day
DOI	RCS	19.4 m/s
PDI Settling Burn	RCS	2.2 m/s
Breaking Burn	MPS	1,798.9 m/s
Guidance Phase	MPS	216.9 m/s
PDI Dispersion	MPS	53 m/s
Approach Redesignation	MPS	3 m/s
Descent RCS	RCS	11 m/s

Validation: Altair Vehicle GR&A

- Basic vehicle information was gathered from literature [22] [25] [15]
- Assumptions were used to satisfy any remaining gaps in the vehicle input values

Avionics

- Avionics suite consists of
  - Reaction wheels (3)
  - Control moment gyros (6)
- Sensing equipment:
  - Gyros (3)
  - Star scanners (3)
  - Magnetometer
  - Terrain and hazard navigation

Power

- Power storage provided by rechargeable Li-Ion batteries
  - Sized to provide additional power requirement for transition LLO → lunar surface
  - Additional two batteries carried for redundancy

Structures

- A structure percentage of 42% is used for the Altair DM [15]

Tanks

- Tank configuration consists of 4 LOX and 4 LH2 tanks (L/D ratios of 2.0 and 3.5, respectively)
- Fuel cell reactants are stored within the MPS tanks (3%)
- Propellants are positioned for delivery to the engine via propellant settling maneuvers (removes the need for a LAD)

Thermal Control

Engines

- Modeled using characteristics of an RL-10
  - Thrust: 83.0 kN
  - Isp: 448.6 sec
  - OFR: 6.0
- RCS uses four sets of four 100 N NTO/MMH thrusters
  - Isp: 300 sec
  - OFR: 1.75

Validation: Altair Thermal Control GR&A

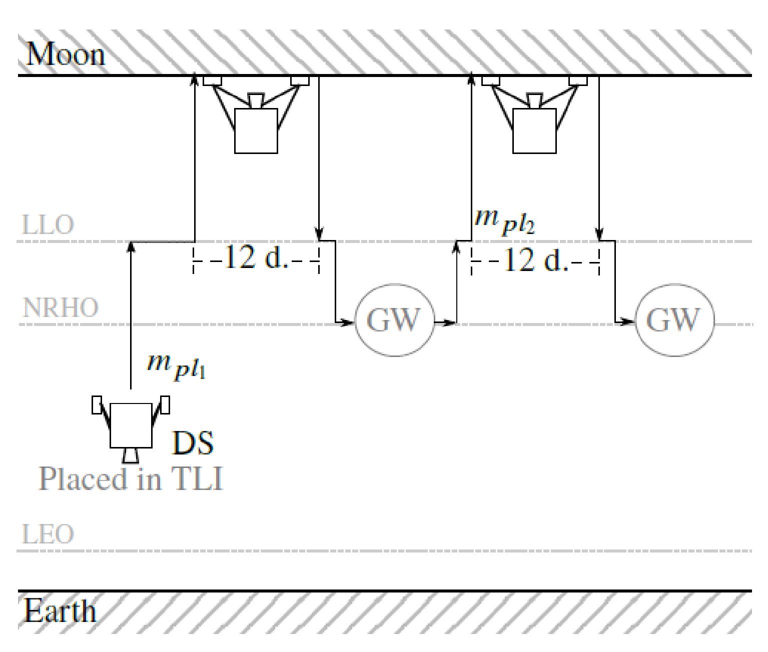
- Approach
  - Thermal control of cryogenic propellants is accomplished via passive methods alone
  - The passive system consists of MLI and SOFI
  - Each tank incorporates:
    - 30 layers of variable density MLI
    - SOFI with a 25mm thickness [5] and a density of 36.8 kg/m3
- Thermal Environment
  - Altair spends its time both in-space and on the lunar surface
  - Most thermally constraining of these two environments is the lunar surface
  - Lunar surface properties:
    - Surface temperature: 207 K
    - Surface albedo: 0.12 [22]
    - *Beta angle: 0° [26]

Validation Results

- The lunar lander suite of contributing analyses was validated against the Altair descent module (DM)
- Calculated masses from M&S environment:
  - Vehicle dry mass: 6,421 kg
  - Total vehicle mass: 37,513 kg (with margins)
  - 7.8% difference in actual vs. calculated
- Passive boil-off rates:
  - LH2: 1.4 %/day
  - LOX: 0.2 %/day
- Results of validation case increases confidence in the sizing capability of the M&S framework

Category	Sub-Category	Values (kg)	
		Altair[27]	DYREQT
Avionics	C&DH	202.7	–
	C&T	10.8	–
	GN&C	48.4	–
	Subtotal	261.8	262.2
Structures	**Subtotal**	2,655.7	2,856.5
Non-Prop Fluids	Fuel Cell Reactants	–	932.8
	Other	–	278.2
	Subtotal	1,211.0	1,211.0
Power	Fuel Cells	273.9	440.9
Propellant	for ΔV	24,890.1	26,616.9
Propulsion	Tanks	–	1,825.4
	Engines	–	314.4
	Subtotal	2,513.2	2,995.6
Thermal	CFM	–	515.7
	Radiator	–	259.0
	Subtotal	499.4	1,101.8
EVA	Equipment	5.1	–
Vehicle	Dry Mass	6,204.0	6,801.2
	Inert Mass	7,420.0	7,632.2
	Subtotal	32,310.1	34,944.2
	MGA	20%	20%
	MR	20%	20%
	Total	34,791.0	37,513.48

Reusable Lunar Lander



- Exercise the DYREQT lunar lander environment to design a lunar lander
- Two sizing missions
  - Deployment
    - Placed in TLI by launch vehicle
    - Performs insertion into LLO
    - Performs all maneuvers to spend 12 days on the lunar surface
    - Returns to NRHO
  - Reuse:
    - Lander refuels in NRHO
    - Performs all maneuvers to spend 12 days on lunar surface
    - Returns to NRHO
- Key constraints:
  - LV TLI capacity of 16,000 kg
  - LV dynamic envelop of 6.35m
- Objective function
  - Want to size vehicle to deployment mission while maximizing the payload of the reuse mission

$$minimize\left(\frac{m_{gross}}{p_{deployment} + 0.1p_{reuse}}\right)$$

Reusable Lunar Lander Results

- Vehicle architecture
  - LOX/LH2 main engine with an Isp of 450 seconds
    - Rubberized engine– weight scaled by thrust
    - Four propellant tanks (two fuel, two oxidizer)
  - 100 lbf NTO/MMH RCS thrusters with an Isp of 300 seconds
  - Reduced boiloff cryogenic fluid management system
    - Zero boiloff LOX, reduced boiloff LH2
    - Single dedicated cryocooler with broad area cooling shields
    - 30 layers of MLI
  - Photovoltaic power generation
    - Batteries sized to one-hour LLO eclipse
    - Assumed that cryocoolers can throttle down during eclipse

Category	Mass (kg)
Avionics	217
Structures	909
Power	390
Tanks	647
Engines	213
Thermal Control	652
Total Dry	3030
MGA	757
Inert Mass	3788
Deployment Mission	
MPS Propellant	10733
RCS Propellant	358
Wet Mass	14879
Payload Mass	1120
Gross Mass	16000
Reuse Mission	
MPS Propellant	10774
RCS Propellant	307
Wet Mass	14869
Payload Mass	1732
Gross Mass	16601

Conclusions

- DYREQT is a specialization of OpenMDAO for the sizing and synthesis of space transportation systems
- This work utilized DYREQT to size a lunar lander
- Special attention paid to thermal control subsystems due to in-space loiter requirements
  - Integrated external analysis of CryoSIM to size active cooling systems
- Showed validation vs Altair lander and demonstrated multi-point sizing of reusable cargo lunar lander